ELSEVIER

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Energy Procedia 37 (2013) 7186 – 7198

Energy Procedia

GHGT-11

Deployment of CCS in industrial applications in the EU – timing, scope and coordination

Johan Rootzén[a,]*, Filip Johnsson[a]

[a]*Department of Energy and Environment, Energy Technology, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden*

Abstract

This paper discusses the potential contribution of CCS as a means to drastically reduce carbon dioxide emissions from carbon-intensive industries in the EU up to 2050. We assess how capital stock turnover influences the penetration rate of CCS and estimate the increases in the energy demand of the industries under different scenarios for the deployment of CO_2 capture. The analysis covers petroleum refining, iron and steel production and cement manufacturing in the EU-27 and Norway. A previous study by the authors suggests that total emissions from the assessed sectors will exceed the targeted levels by more than twofold unless a major breakthrough in low-carbon process technologies materializes within the period up to 2050. The results of the present study demonstrate that deployment of CCS, from the year 2030, can substantially contribute to reducing CO_2 emissions deriving from carbon-intensive industries. We show how an ambitious deployment of CO_2 capture in carbon-intensive industries, in combination with extensive implementation of abatement measures currently available, could result in a 80% reduction in CO_2 emissions by 2050, as compared to levels in 2010. However, the results also highlight how a large-scale introduction would come at a high price in terms of energy use.

Keywords: CO_2 capture; refinery; iron and steel; cement; deployment; CCS; industry; EU; energy use

1. Introduction

In February 2011 the European Council reconfirmed the EU objective of reducing greenhouse gas emissions by 80-95% by 2050 compared to the 1990 emission levels. Meeting this challenge will require commitment across all sectors of society. Carbon-intensive industries contribute to a significant share of the anthropogenic CO_2 emissions in the EU. A relatively small number (~300) of large refineries, iron and

* Corresponding author. Tel.: +46(0)31-7725251; fax: +46(0)31-7723592.
E-mail address: johan.rootzen@chalmers.se.

1876-6102 © 2013 The Authors. Published by Elsevier Ltd.
Selection and/or peer-review under responsibility of GHGT
doi:10.1016/j.egypro.2013.06.656

steel plants and cement industries together account for approximately 8% of EU's total GHG emissions. However, measures to drastically reduce the CO_2 emissions associated with the production of refined petroleum products, iron and steel and cement are limited if restricted to proven best available technology. Yet, CCS is recognized as a promising option for CO_2 mitigation from centralized emission sources such as the industrial processes assessed here. Our previous work indicates that, despite optimistic assumptions regarding the potential for, and implementation of, available abatement strategies within current production processes, EU carbon-intensive industries will fail to comply with more stringent emission reduction targets in the medium- and long term [1], as shown in Figure 1. Thus, to realize the goals of further, extensive, emission reductions, efforts to develop and deploy low carbon production processes must be intensified. A first estimate by the authors of the potential for CO_2 capture in European industry shows that considerable emission reductions (60 – 75%) can be achieved if large point sources in the most emission intensive branches (i.e. mineral oil refineries, integrated steel plants and cement plants) are targeted [2].

Building on our previous studies, the work presented in this paper has the aim to assess the implications of the timing and scope of a large-scale implementation of CCS in industrial sources in the EU. Based on the age structure of the existing capital stock in the EU refining-, steel- and cement-industries we assess: (a) how capital stock turnover influence the penetration rate of CCS in industrial applications, and (b) the effects on industry energy use of different scenarios for the scope of the deployment of CO_2 capture.

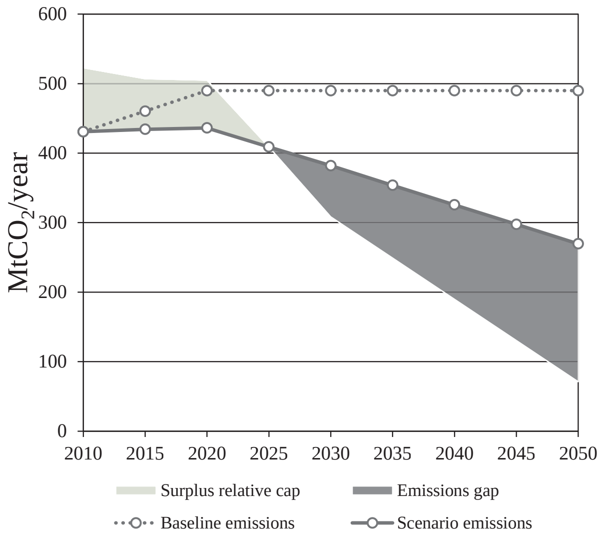

Fig. 1. Estimated 'best-case' emissions trajectory (solid line) for EU carbon-intensive industries, if restricted to proven best available technology, relative to the baseline case (dashed line) in which technology and fuel mixes are frozen at 2010 levels [1]. The light-grey and grey wedges indicate deviation from an indicative emissions cap.

2. Methodology

The analysis covers petroleum refining, iron and steel production, and cement manufacturing in the EU-27 and Norway. The most distinctive feature of the analysis is the treatment of capital stock turnover. By simulating capital stock turnover, scenarios that incorporate changes in technology stock, energy intensities, fuel and production mixes, and the resulting development of CO_2 emissions have been assessed for each industry branch. Capital stock turnover is simulated up to the year 2050 for each branch based on the age structure of the existing capital stock and assumptions regarding the average technical lifetime of key process technologies.

2.1. Basic assumptions

The scenarios, one for each branch, which form the basis for the assessment of the role of CO_2 capture, describe the development of key characteristics and trends governing future energy use and CO_2 emissions. The individual scenarios have been generated based on branch- and technology-specific parameters and boundary conditions. Key inputs include assumptions on future development of, activity levels, structures of production, fuel mixes and technology characteristics.

Scenario inputs related to abatement measures other than CCS are described in detail in [1] where inputs have been chosen to reflect a development in which ambitious measures are taken to exploit the abatement strategies currently available in each sector (excluding CO_2 capture).

2.1.1. Future activity levels and production mix

Transformation of the transport sector (penetration of alternative fuels and powertrains) and reduced demand for petroleum products in other end-use sectors are assumed to lead to an overall reduction in refinery throughput from 670 Mt in 2010 to 283 Mt in 2050 [3, 4]. It is assumed that there will be no major changes in the overall demand for crude steel and cement. Total steel production is assumed to increase from 170 Mt steel/year in 2010 to 200 Mt steel/year (comparable to the production levels prior to the current economic crisis) and thereafter remain constant throughout the period studied. Secondary steelmaking (i.e.in Electrical Arc Furnaces) is assumed to continue to gain market shares while the share of the integrated steel plants in the EU steel production is assumed to continue to decrease in line with the historical trend, from 58% in 2010 to 38% in 2050. Cement production is assumed to increase from 190 Mt/year in 2010 to 240 Mt/year in 2020 and to remain constant thereafter.

A common feature of all of the branches assessed herein is an ageing capital stock. Thus, a large share of the existing capital stock will need to undergo major refurbishment or replacement over the coming decades.

For the primary steel- and cement industries the pace of capital stock turnover is assessed based on the industries age structure and the assumed average technical lifetime of key process equipment is set to 50 years. In the refining industry, new investments are assumed to be in desulfurization units or advanced conversion units; no new investments in primary refining capacity take place. While all petroleum refineries undertake crude oil distillation, the specific configuration of further processing varies among individual refineries. For simple refineries, involving fewer processing steps, the output mix is almost entirely fixed by the type of crude being processed. More complex refineries, involving several processing steps, have a higher conversion capacity and a higher flexibility with regards to crude intake. Here EU refineries have been divided into four categories depending on their configuration (Configurations 1-4 [5, 6]). Complex refineries (Configurations 3 and 4) share of the total transformation output increase at the expense of simpler refineries with less flexibility and conversion capacity (Configurations 1 and 2).

Table 1. Scenario summary - activity levels and production mix.

	2010	2020	2050	Specific energy use (GJ/t output)
Petroleum refining[a]				
Total transformation throughput (*Mt/year*); of which	670	612	280	
- Configurations 1 and 2	63	55	0	1.7 – 2.8
- Configurations 3 and 4	37	45	100	2.8 – 3.7
Iron and steel industry[b]				
Primary steel (BF/BOF) (*Mt steel/year*); of which	100	108	77	
- Existing capacity (%)	100	61	5	17 – 23
- New capacity (%)	0	39	95	16.5
Cement manufacturing[c]				
Total cement production (*Mt cement/year*); of which	190	240	240	
- Existing capacity (%)	100	64	6	3.6 – 5.7
- New capacity (%)	0	36	94	3.1

[a] Total transformation output in 2010 from [7]. Estimated share of annual throughput, by refinery configuration type, based on [5]. Specific energy use by refinery configuration type, estimated based on [5, 8].
[b] Data on crude steel production in 2010 are taken from [9]. Age structure of current capital stock estimated based on [10]. Specific energy use by vintage class, estimated based on [11–14].
[c] Cement production data for 2010 obtained from [15]. Age structure of current capital stock estimated based on [16, 17]. Specific energy use by kiln type, estimated based on [18, 19].

2.1.2. CO_2 capture options

To date, most work on CCS for applications in the carbon-intensive industry sectors has been focused on two technical options for CO_2 capture [e.g. 20–22]:

- Post-combustion capture (PC), were CO_2 is separated from the flue gases through chemical or physical absorption or carbon selective membranes.
- Oxyfuel combustion (OF), were fuel is combusted in oxygen (mixed with recirculated flue gas) instead of air, creating a more or less pure CO_2 stream in the off gases.

In principle, both of these technical options are applicable to the industrial processes examined in this study. Post combustion capture through chemical absorption could be applied to almost all industrial processes. Process specific capture technologies could, however, provide more cost effective options. Table 2 summarizes the key characteristics of the CO_2 capture options considered in the analysis.

Table 2. Key characteristics of the CO_2 capture options considered in the analysis. *CO_2 emissions avoided* gives – the emission reductions achieved relative to a reference plant without CCS. *Thermal energy* – gives the specific thermal energy use, including the energy penalty related to CO_2 capture, per tonne of output. Correspondingly, *Electricity* – provide the specific electricity use, including the additional electricity use associated with CO_2 capture, per tonne of output.

	Targeted emission source	CO_2 emissions avoided (%)	Thermal energy (GJ/t output)	Electricity (kWh/t output)
Petroleum refining[a]				
Post combustion (PC)	Combined stack + FCC/Hydrogen plant	60	6.1 – 7.1	107 – 145
Oxyfuel combustion (OF)	Furnaces and boilers	60	2.8 – 3.7	440 – 478
Iron and steel industry[b]				
Top Gas Recycling Blast Furnaces (TGR-BF).	Blast furnace	60	16.5	333
Cement manufacturing[c]				
C1: Post combustion (PC)	Kiln + Precalciner	92	6.1	180
C2: Partial oxyfuel (POF)	Precalciner	65	3.5	200
C3: Full oxyfuel (FOF	Kiln + Precalciner	92	3.2	224

[a] The authors own estimations based on [20–22].
[b] The authors own estimations based on [22–25].
[c] The authors own estimations based on [22, 26–28].

In all industries CO_2 capture is assumed to be available at a commercial scale from 2030. While an earlier introduction seems unlikely at the current rate of development introduction at a later point would limit the prospects for CCS to contribute to substantially reducing CO_2 emissions up to 2050.

2.1.3. Costs

Since practical experiences of CCS in industrial applications, with a few exceptions, are still largely lacking, cost estimates are associated with significant uncertainties. Some general insight can however be drawn from the existing literature [20–34]:

- With the exception of a few high-purity CO_2 sources (e.g. natural gas processing, hydrogen production and ammonia production) abatement costs associated with capture in industrial applications are generally in the high-cost end of the portfolio of abatement measures available to industry.
- Cost estimates tend to have been adjusted upwards in more recent studies (see e.g. [22, 23, 33]).
- Costs associated with transportation and storage will be significantly higher if CCS were to be introduced in the industry sector without coordination with the power sector (see e.g. [30]).

- While policy support plays an important role in the development and deployment of many low-carbon technologies, it is especially crucial for CCS. This is because, in contrast to for example renewable energy and energy efficiency measures, CCS generates no income, nor provides any other market incentives, as long as the cost of emitting CO_2 remains low [34].

The current analysis is restricted to the technical potentials of possible capture options and thus, it largely ignores possible economical and institutional constraints.

2.2. Branch-specific assumptions

2.2.1. Petroleum refineries

Data on the age distribution of equipment stocks in the refinery industry is rarely disclosed and the specific configuration varies across individual refineries. As described above, simpler refineries are assumed to be gradually phased out over the period studied. Thus, CCS deployment in EU refinery industry is assumed be limited to more complex refineries and to consist entirely of retrofits. Three cases for the deployment of CO_2 capture in the petroleum refining industry have been analyzed:

- R0: Represents the base case where CCS is not included as an alternative, thus, measures to reduce CO_2 emissions are restricted to proven best available technology.
- R1: Post-combustion is assumed to be applied to a combination of sources within the refinery complex with flue gas CO_2 concentrations suitable for chemical absorption, e.g. applying capture to combined stack (collecting flue gases from several furnaces and/or boilers), catalytic cracker and/or hydrogen plant (together the sources targeted for CO_2 capture are assumed to represent approximately 60% of the total CO_2 emissions from the refining process).
- R2: Heaters and boilers are converted to oxyfuel operation with CO_2 capture.

To distinguish the effects of the respective CO_2 capture option, the set-up is assumed to be similar across all EU refineries remaining in 2050, and in each of the two cases the dominant capture technology (post-combustion capture in R1 and oxyfuel combustion in R2) is assumed to cover the whole market.

2.2.2. Primary steel production

The Top gas recycling blast furnace (TGR-BF) is assumed to offer the most promising prospects of applying CO_2 capture without disrupting the core production processes in the primary steel industry [Q1, Q3]. Three cases for the deployment of CO_2 capture in the primary steel industry have been analyzed:

- S0: Represents the base case where CCS is not included as an alternative, thus, measures to reduce CO_2 emissions are restricted to proven best available technology.
- S1: Retrofit is not included as an option, thus, the rate of deployment of CCS depends on the rate of turnover of existing blast furnaces. Here TGR-BF fitted for CO_2 capture is assumed to be the standard for blast furnaces commissioned from the year 2030.
- S2: The possibility to retrofit existing blast furnaces is included as an option. As in case S1, TGR-BF with CO_2 capture is the standard for new blast furnaces, in addition, all remaining blast furnaces commissioned before 2030 are retrofitted to meet the same standard.

2.2.3. Cement industry

Two options for CO_2 capture in the European cement industry have been considered. Post-combustion capture can be applied utilizing the same basic principles that are being developed for coal-fired power plants. Oxy-combustion with CO_2 capture can be applied both in the precalciner and in the cement kiln (full oxyfuel); by targeting the precalciner only (partial oxyfuel), the impacts on the clinkerization process can be minimized. Five cases for the introduction of CO_2 capture in the EU cement industry have been analyzed:

- C0: Represents the base case where CCS is not included as an alternative, thus, measures to reduce CO_2 emissions are restricted to proven best available technology.
- C1: Cement kilns fitted with post-combustion capture are assumed to be the standard for new capacity commissioned from the year 2030.
- C2: Cement kilns fitted for partial oxy-combustion are assumed to be the standard for new capacity commissioned from the year 2030.
- C3: Cement kilns fitted for full oxy-combustion are assumed to be the standard for new capacity commissioned from the year 2030.
- C4: Cement kilns fitted for full oxy-combustion are assumed to be the standard for new capacity commissioned from the year 2030, in addition, all remaining cement plants commissioned before 2030 are retrofitted with post-combustion capture.

It should be noted that in C1–C3 retrofit is not included as an option, thus, the rate of CCS deployment will depend on the rate of turnover of existing cement plants.

3. Results

As described above, the scenarios that form the basis for the assessment of deployment of CCS in industrial applications postulate a development in which ambitious measures are taken to exploit the abatement strategies currently available in each sector. This includes assuming moderate (cement) or negative (petroleum products and secondary steel) output growth, an almost complete renewal of the capital stock (with the exception of the petroleum refining industry) and extensive implementation of proven best available technology. This section presents the results of the analysis of the effects of different options for the deployment of CCS in industrial application, to reduce further industry CO_2 emissions.

3.1. Petroleum refineries

Figure 2 shows the estimated annual CO_2 emissions from EU refineries over the period studied, for the cases without (R0) and with (R1 and R2) introduction of CCS together with the total thermal and electrical energy use. In the base case (R0) where CCS is not implemented CO_2 emissions are reduced from 130 $MtCO_2$/year in 2010 to 65 $MtCO_2$/year in 2050. Similarly, total thermal and electric energy use is reduced, from 1890 to 970 PJ/year and from 72 to 38 TWh/year, respectively. In the base case, reductions of CO_2 emissions and energy use are primarily a result of the envisaged drop in total output from EU refineries, from 670 Mt/year in 2010 to 280 Mt/year in 2050. In the two cases where CO_2 capture is included as alternative (R1 and R2) CO_2 emissions are reduced further from 130 $MtCO_2$/year in 2010 to approximately 25 $MtCO_2$/year in 2050. However, the additional CO_2 abatement would come at the price of increased energy use. In case R1, where post-combustion capture is assumed to be the technology of choice, total annual thermal energy use in 2050 is in level with thermal energy use in 2010, approximately 1900 PJ/year. In case R2 where oxyfuel combustion is assumed to be the preferred capture technology, total electric energy use in 2050 is 132 TWh/year in 2050 compared to 73 TWh/year in 2010. This despite the assumed decline in total output of petroleum products from EU refineries in the same period.

The assumptions that simpler refineries are gradually phased out, and, that effects of energy efficiency improvements are outweighed by expansions of the conversion and treatment capacities, result in an increase in specific energy use (GJ/t throughput) in all cases (R0–R2). In the base case (C0) average specific thermal energy use increases from 2.8 GJ/t throughput in 2010 to 3.4 GJ/t throughput in 2050. In the case where post-combustion capture is assumed to be the technology of choice for CO_2 capture (R1) energy penalties, associated primarily with capture solvent regeneration, lead to an increase in specific thermal energy use from 2.8 GJ/t throughput in 2010 to 6.8 GJ/t throughput in 2050. Correspondingly in case R2, energy used for air separation, is the main driver behind the increase in specific electricity use, from 110 kWh/t throughput in 2010 to 465 kWh/t throughput in 2050.

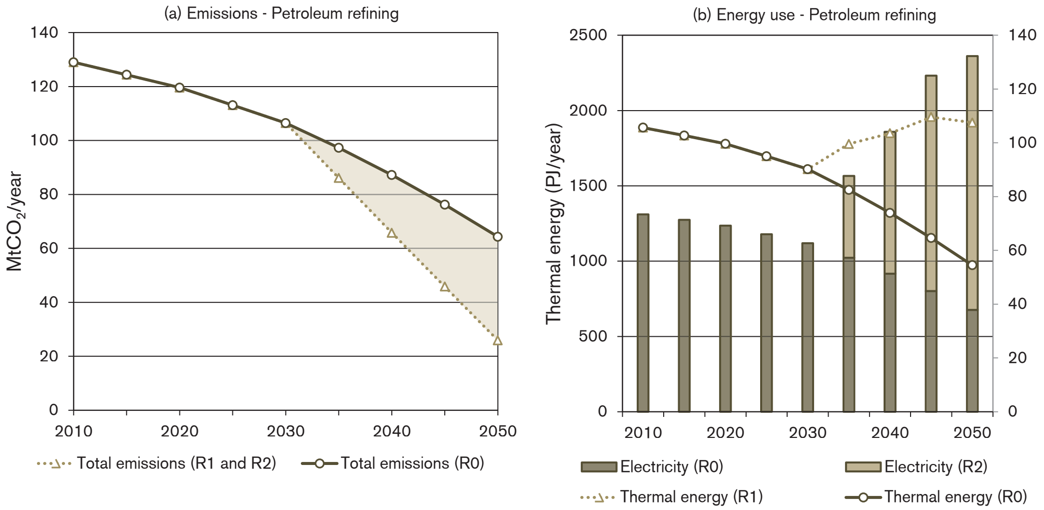

Fig. 2. Estimated CO_2 emissions and energy use from the EU petroleum refining industry in the period 2010–2050 as obtained from this work. The base case (R0) assumes extensive implementation of abatement strategies currently available but no deployment of CCS. Case R1 (post-combustion) and R2 (oxyfuel combustion), in addition to the abatement measures in the base case, assume deployment of CO_2 capture. (a) The estimated CO_2 emissions from European refineries in the period 2010–2050, with (dashed line) or without (solid line) introduction of CCS. (b) The estimated development of thermal (solid/dashed lines) and electrical (bars) energy use with (light brown) or without (brown) introduction of CCS.

3.2. Primary steel production

Figure 3 presents the projected CO_2 emissions trajectories together with aggregated thermal and electrical energy use for EU integrated steel plants (2010–2050), for the case without introduction of CCS (S0) and for the case with the most ambitious deployment of CCS (S2). When retrofit is excluded as an option (S1) the contribution of CCS to total emissions reductions remains limited. Estimated emissions in 2050 are 79 $MtCO_2$/year in case S1 compared to 87 $MtCO_2$/year in case S0. In case S2, where TGR-BF's fitted for CO_2 capture are assumed to be gradually introduced in all integrated steel plants from the year 2030, CO_2 emissions are reduced from 180 $MtCO_2$/year in 2010 to 36 $MtCO_2$/year in 2050. The ambitious deployment of CO_2 capture in S2 has limited effect on overall thermal energy use since the TGR-BF consumes less coke than a conventional blast furnace. However the loss of blast furnace gas and investments in CO_2 separation and compression result in a significantly higher electric energy use in S2 than in S0. Total electric energy use in S2 in 2050 is 25 TWh/year, which is more than twice the electricity use in S0 in the same year. In the base case (S0) specific electricity use is gradually reduced, from an average level of 333 kWh/t steel in 2010 to 165 kWh/t steel in 2050, as existing technology stock is replaced with state-of-the-art processes equipment. In case S2, the introduction of CO_2 capture from the year 2030 result in an increase of specific electricity use back to the present (2010) levels.

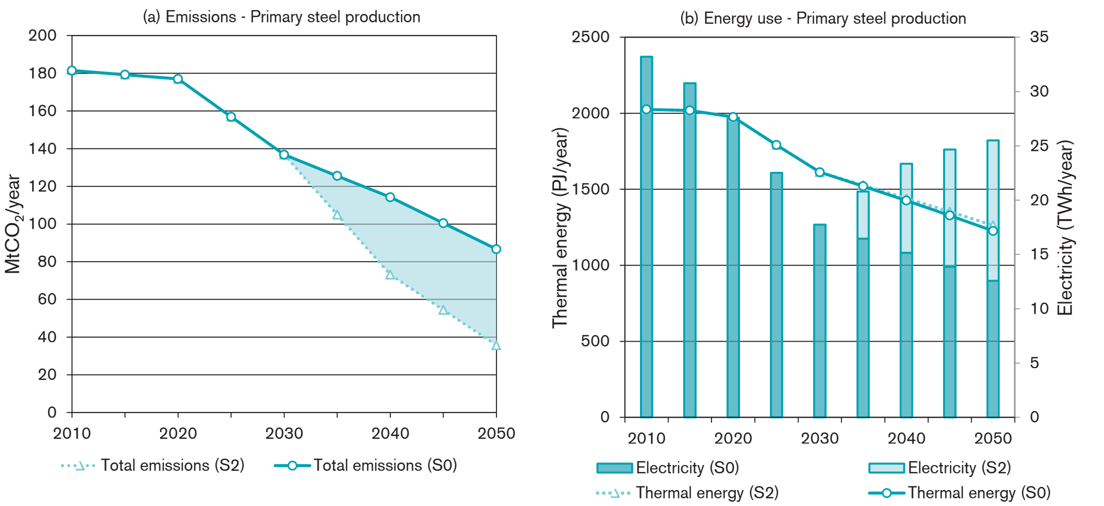

Fig. 3. Evolution of CO_2 emissions and energy use in the EU primary steel industry for the period 2010–2050 as obtained from this work. Case S0 assumes extensive implementation of abatement opportunities currently available but no deployment of CCS. Case S2 in addition to the emissions reduction measures implemented in S0, assume TGR-BF's fitted for CO_2 capture to be deployed at all remaining integrated steel plants in the EU throughout the period, 2030–2050. (a) The estimated cumulative CO_2 emissions from EU primary steel production with (dashed line) or without deployment of CCS (solid line). (b) The estimated development of thermal (solid/dashed lines) and electrical (bars) energy use with (light blue) or without (blue) introduction of CCS.

3.3. Cement industry

Figure 4 presents the projected CO_2 emissions trajectories together with aggregated thermal and electrical energy use for EU cement plants over the period studied for the case without introduction of CCS (C0) and for the case with the most ambitious deployment of CCS (C4). In the cases where retrofit of CO_2 capture to the kiln system (or a part of the kiln system) is not considered (C1–C3) the contribution of CCS to total emissions reductions remains limited. In C4, where kiln systems fitted for full oxy-combustion are assumed to be the standard for new capacity from the year 2030 and where cement plants commissioned prior to that year are retrofitted with post-combustion capture, total CO_2 emissions are reduced from 127 $MtCO_2$/year in 2010 to 18 $MtCO_2$/year in 2050. In this case, the energy penalty associated with CO_2 capture results in a total thermal energy use of 1265 PJ/year and a total electricity use of 44 TWh/year in 2050.

In the base case (C0) average thermal energy consumption of the cement kiln stock is reduced from 3.8 GJ/t to 3.1 GJ/t clinker over the period studied as old kilns are replaced with state-of-the-art kilns. Similarly, gradual improvements and replacements of e.g. grinders and fans, lead to a decrease in specific electricity use from an average level of 118 kWh/t clinker in 2010 to 97 kWh/t clinker in 2050. Large-scale deployment of CO_2 capture (case C4) would result in a significant increase in specific energy use. In this case specific thermal energy use amounts to 5270 GJ/t clinker and electricity use to 182 kWh/t clinker in 2050.

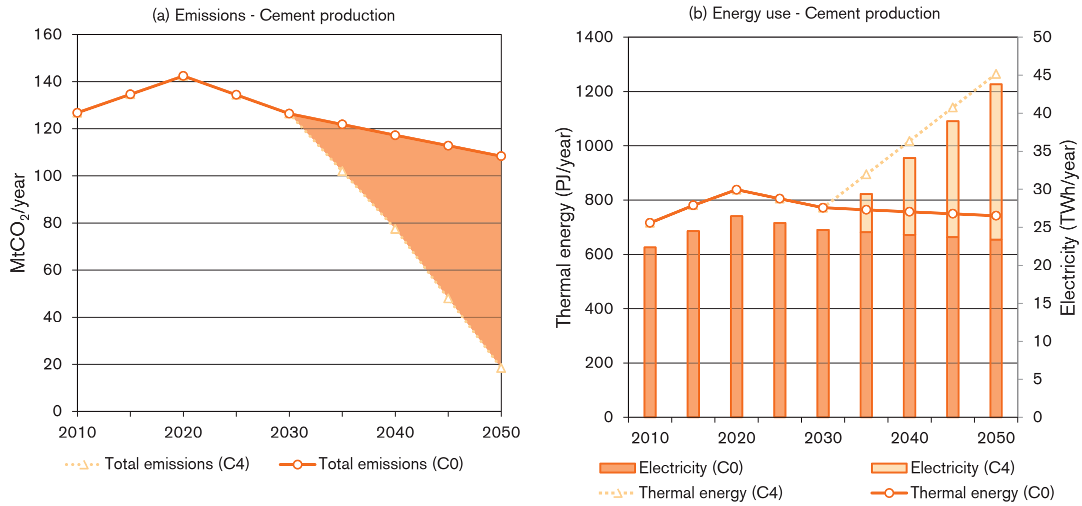

Fig. 4. Estimated CO_2 emissions and energy use from the EU cement industry, 2010–2050 as obtained from this work. Case C0 assumes ambitious implementation of available mitigation measures but excludes CCS as an abatement option. In case C4, from the year 2030, cement kilns fitted for full oxycombustion are assumed to be the standard for new capacity, in addition, all remaining cement plants commissioned before this year are retrofitted with post-combustion capture. (a) The estimated annual CO_2 emissions from EU cement manufacturing, 2010 – 2050, with (dashed line) or without (solid line) introduction of CCS. In both cases total emissions include both fuel-related and process-related emissions. (b) Gives the estimated development of thermal (solid/dashed lines) and electrical (bars) energy use with (light orange) or without (orange) introduction of CCS.

3.4. Summary

Given the assumptions in this study it can be concluded that combining the most ambitious deployment trajectories in each of the industries investigated result in an 80% CO_2 emission reduction, from 440 $MtCO_2$/year in 2010 to 80 $MtCO_2$/year in 2050. However this will also result in a continued high energy use. Combining the cases R1 (refinery), S2 (steel) and C4 (cement) results in a total thermal energy demand for the three industries of 4450 PJ year in 2050 compared with 4630 PJ/year in 2010 (roughly 40% of industry final energy use). This in spite of assuming moderate (cement) or negative (petroleum products and primary steel) output growth over the period studied. Correspondingly, combining deployment trajectories R2, S2 and C4 results in a total electricity use of 200 TWh/year in 2050 compared to 130 TWh/year in 2010.

The results also show the importance of overcoming barriers to retrofit of CO_2 capture to the assessed industrial processes. The simulated stock turnover suggests that a majority of the existing EU primary steel and cement production capacity will undergo major refurbishments or be replaced in the period up to 2030. As a consequence, in the cases (S1 and C1–C3) where retrofit is not included as an option the contribution of CCS to total emissions reduction is limited.

4. Conclusions

From the results presented in this paper it can be concluded that achieving deep reductions in CO_2 emissions (~85% reduction by 2050, as compared to levels in 1990) within the industry branches investigated in less than four decades will be a significant challenge. Without CCS, total emission levels in 2050 from the industries examined in this work will exceed by more than twofold the targeted levels. An ambitious introduction of CO_2 capture is estimated to be able to reduce emissions to levels in line with the targets for 2050. The results also highlight how an extensive ramp-up would come at a high price in terms of energy use. The results indicate that a large-scale deployment of CCS largely offset the gains of previous efforts to improve energy efficiency. This suggests that for these industries, unless other alternative low-carbon production processes emerge, there may be a trade-off between CO_2 emission reduction and reduced energy requirements in the longer-term.

Acknowledgements

The work presented in this paper been carried out within the framework of the Pathways to Sustainable European Energy Systems project which is aimed at evaluating pathways to a sustainable European energy system, focusing on the stationary energy system and the time period up to the year 2050. Co-funding from the Swedish Energy Agency is gratefully acknowledged.

References

[1] Rootzén J, Johnsson F. Exploring the limits for CO_2 emission abatement in the EU power and industry sectors - Awaiting a breakthrough. Manuscript submitted for publication (2012).

[2] Rootzén J, Kjärstad J, Johnsson F. Prospects for CO_2 capture in European industry. *Management of Environmental Quality: An International Journal* 2011;**22**(1):18–32.

[3] European Commission, 2011b. Commission staff working document, Impact assessment, Accompanying document to the: Communication from the commission of the European Parliament, the Council, the European Economic and Social Committee and The Committee of the Regions, A Roadmap for moving to a competitive low carbon economy in 2050, SEC(2011) 288 final, Brussels, 8.3.2011.

[4] Europia, 2011. 2030-2050 Europia contribution to EU energy pathways to 2050.The European Petroleum Industry Association (Europia), Brussels, Belgium.
[5] European Commission. Best Available Techniques (BAT) Reference Document for the Refining of mineral oil and gas (Draft document). Integrated Pollution Prevention and Control (IPPC)-European Commission, Joint Research Centre, European IPPC Bureau, Seville, Spain, (Draft) 2012.
[6] Koottungal L. 2007 Worldwide refining survey. Oil & Gas Journal 2007;Dec. 24.
[7] Eurostat, 2011b. Transformation output from Refineries, Supply, transformation, consumption - oil - annual data. Eurostat Statistics database. (Accessed 10 October 2012). URL: <epp.eurostat.ec.europa.eu>
[8] CONCAWE. EU refinery energy systems and efficiency. The oil companies' European association for Environment, Health and Safety in refining and distribution, Conservation of clean air and water in europe (CONCAWE), report no. 3/12. Brussels, Belgium, March 2012.
[9] WSA. Steel Statistical Yearbook, World Steel Association (WSA), 2011.
[10] Steel Institute VDEh. Description of the Plantfacts database, Steel Institute VDEh, Technical information department and Library, 2009.
[11] European Commission. Best Available Techniques (BAT) Reference Document for Iron and Steel Production. Integrated Pollution Prevention and Control (IPPC). European Commission, Institute for Prospective Technological Studies, European IPPC Bureau, Seville, Spain, 2012
[12] European Commission. Final Report of the SET-Plan workshop on Technology Innovations for Energy Efficiency and Greenhouse Gas (GHG) emissions reduction in the Iron and Steel Industries in the EU27 up to 2030. European Commission Directorate-General Joint Research Centre, Petten, The Netherlands, 2010.
[13] Worrell E, Price L, Neelis M, Galitsky C, Nan Z. World Best Practice Energy Intensity Values for Selected Industrial Sectors. Ernest Orlando Lawrence Berkeley National Laboratory, Environmental Energy Technologies Division, LBNL-62806 REV. 2, February 2008.
[14] Fruehan RH, Fortini O, Paxton HW, Brindle R. Theoretical Minimum Energies to Produce Steel for Selected Conditions. Carnegie Mellon University, Pittsburgh, PA; 2000.
[15] Cembureau. Cement production in CEMBUREAU and EU27 countries. The European Cement Association, Cembureau, Brussels, Belgium, 2012.
[16] Cembureau.World Cement Directory 2002. The European Cement Association, Cembureau, Brussels, Belgium, 2001.
[17] GCD. Global Cement Directory 2009, Pro Publications International Limited, Epsom, Surrey, United Kingdom, 2009.
[18] WBCSD. Cement Industry Energy and CO_2 Performance – "Getting the Numbers Right". World Business Council for Sustainable Development (WBCSD) Cement Sustainability Initiative. (Accessed 12 September 2012). URL:<wbcsdcement.org/GNR-2009>
[19] European Commission. Draft Reference Document on Best Available Techniques in the Cement, Lime and Magnesium Oxide Manufacturing Industries, Integrated Pollution Prevention and Control, Joint Research Centre, European Commission, Seville, Spain, 2010.
[20] van Straelen J, Geuzebroek F, Goodchild N, Protopapas G, Mahony L. CO_2 capture for refineries, a practical approach. *International Journal of Greenhouse Gas Control* 2010;**4**(2):316-20.
[21] Allam R, White V, Ivens N, Simmonds M. Chapter 26-The oxyfuel baseline: revamping heaters and boilers to oxyfiring by cryogenic air separation and flue gas recycle, Carbon dioxide capture for storage in deep geologic formations. Amsterdam: Elsevier Science; 2005. p. 451-75.
[22] Kuramochi T, Ramírez A, Turkenburg W, Faaij A. Comparative assessment of CO_2 capture technologies for carbon-intensive industrial processes. *Progress in Energy and Combustion Science* 2012;**38**:87–112.
[23] United Nations Industrial Development Organisations (UNIDO). Sectoral assessment for the iron and steel sector., Jean-Pierre Birat (ArcelorMittal), United Nations Industrial Development Organisation. Vienna, Austria, 2010.
[24] Bitat JP, Lorrain JP, de Lassat Y. The "CO_2 Tool": CO_2 Emissions & Energy Consumption of Existing & Breakthrough Steelmaking Routes. *Proceedings of the 4th Ulcos seminar*, 1-2 October, 2008.
[25] ULCOS. Ultra-Low Carbon dioxide Steelmaking, more information available at: www.ulcos.org (accessed 21 April 2012).
[26] IEA GHG (2008), "CO2 capture in the cement industry", International Energy Agency Greenhouse Gas R&D Programme, technical study, Report Number 2008/3.
[27] ECRA. ECRA CCS Project – Report about Phase III. European Cement Research Academy (ECRA). Technical Report, TR-ECRA-106/2009, Duesseldorf, Germany, 2009.
[28] ECRA. ECRA CCS Project – Report on Phase III. European Cement Research Academy (ECRA). Technical Report, TR-ECRA-119/2012, Duesseldorf, Germany, 2012.
[29] OECD/IEA/UNIDO. Technological roadmap – Carbon capture and storage in industrial applications. OECD/International Energy Agency and United Nations Industrial Development Organization. Paris: OECD/IEA/UNIDO; 2011.

[30] Kjärstad J, Ramdani R, Gomes PM, Rootzén J, Johnsson J. Establishing an integrated CCS transport infrastructure in northern Europe – challenges and possibilities. *Energy Procedia* 2011;4:2417–2424.
[31] Herzog, HJ. Scaling up carbon dioxide capture and storage: From megatons to gigatons. Energy Economics 2011;33(4):597–604.
[32] Global CCS Institute. Economic assessment of carbon capture and storage technologies: 2011 update. Canberra, Australia, 2011.
[33] Farla CM., Hendriks CA. and Blok K. Carbon dioxide recovery from industrial processes. *Climatic Change* 1995;**29**(4):439-61.
[34] IEA. Tracking Progress in Carbon Capture and Storage. International Energy Agency (IEA) and the Global CCS Institute report to the third Clean Energy Ministerial, April 2012.